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Review of grid integration schemes for renewable power generation system

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ABSTRACT

Multi-input converters, used to integrate different renewable energy sources, accommodate a range of sources and pools to their advantage such that the energy source is diversified to enhance utilization and reliability of the renewable source. The literature reports the development of several front-end DC–DC converters that could interface the sources. The topologies were classified based on the energy conversion stages, namely, DC–DC boost converter and voltage source inverter, and the kinds of controllers that control the circuit to ensure stabilization of load and input voltage, maintain component tolerance and system ageing. This is a comprehensive study of mapping the progress of diverse inverter topologies from the recent literature. Advantages, disadvantages, and limitations are given in this critical literature survey, along with the basic operating principles of several topologies.

Contents

Abbreviations: DCM, discontinuous conduction mode; FLC, fuzzy logic controller; HM, hysteresis modulation; IEA, International Energy Agency; MV, manipulated variable; MPPT, maximum power point tracking; PV, photovoltaic; PCS, power conditioning system; PID, proportional integral derivative; PWM, pulse width modulation; SPWM, sinusoidal pulse width modulation; SMC, sliding mode control; SVM, space vector modulation; VSCS, variable structure control system theory; ZCS, zero current switching; ZVS, zero voltage switching

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1. Introduction

Renewable energy capacity and the technology to harvest it has grown rapidly over the past decade. Driven by the economic development and associated increasing demand for energy, countries have been looking for ways to utilize the natural resources available to meet the demands. Greenhouse emissions is a crucial threat to the sustainability of the environment driving the governments and policies to arrive at solutions that could produce clean energy and at a reduced cost.

European Union has come forward to reduce the greenhouse gas emission 40% below 1990 levels by 2030. The efforts of other countries also hover to somewhat similar levels: the United States – 25–31%; Japan – 38–48%; Canada – 26–41%; and Russia – 14–27% [1]. China and India have made a voluntary greenhouse emission of 40–45% and 20–25% by 2020 [2,3].

Several options are available to reduce greenhouse emissions. Some can be enumerated as end use efficiency improvement [4,5], fuel switches, reduction of losses during transmission and distribution, and efficiency improvement of existing power plants and new power plants [6].

In India, the energy system is largely based on coal, which means that the expected emissions could surge relatively fast in the future [7]. Nevertheless, India has put enormous effort to improve the efficiency of the electricity production sector with the inclusion of a shift from coal to other fuels, such as renewable energy [8,9].

The renewable energy sources, such as wind, solar, wave energy, hydropower, tidal power, biofuels, and ocean thermal energy conversion, are being considered as efficient alternatives for the fossil fuels. Although many types of alternative or renewable resources are available, this study has limited its focus to photovoltaic (PV) and fuel cells and to propose hybrid alternative energy systems.

The National Solar Mission of India has taken solar power seriously and has been the driving force to make it a chief contributor of future energy mix. The critical mission has substantially supported both the centralized and decentralized power generation, in addition to providing power to rural India for health, education, and employment. At present, the solar power is expensive, i.e., at least three to four times that of coal based power. However, due to the increasing manufacturing capacity, along with support from government, scale deployment, research and development, the cost of the solar power production could reduce to grid parity in the near future. It is one of the crucial technology options that India has to meet the long-term energy security. By 2020, solar power capacity is anticipated to increase to 20,000 MW. India is blessed with good solar radiation in most parts; deploying solar technology even on 1% of the land can generate over 500,000 MW of power [2].

Having understood the necessity of generation of solar power and the capacity available with India, in this study, we have surveyed the literature extensively to find the methods that would bring energy efficiency methods, such as DC–DC boost converters, voltage-source inverter, controllers used for DC–DC converter and controllers used for voltage-source inverters. The review attempts to understand the existing methods available, the deficiency in the methods and the improvement required for these to make it commercially viable.

In Section 2 the DC–DC boost converter categories like DC–DC converter based on the multi-winding transformer, soft switching boost converter and multi-input converters were reviewed. In Section 3 the voltage-source inverter types like bi-directional full-bridge inverter, multilevel inverter and matrix inverter were reviewed. In Section 4 the controllers used for DC–DC converter are depicted in-depth with the advantages of different methods implemented and In Section 5 the controllers used for voltage-source inverter are described in-depth with the merits of different methods adopted. In Section 6 the proposed grid integration scheme for hybrid power generation has been described and Section 7 concludes the work.

2. DC–DC boost converter topologies for hybrid power generation system

Photovoltaic (PV) power generation system has attracted the interest of governments, industry and researchers alike due to its zero greenhouse gas emission. The emissions that are produced while manufacturing its components are the only emissions that are recorded.

Photovoltaic (PV) system consisting of solar cells converts sunlight into electricity through the photoelectric effect. They are being used regularly to supply electricity to individual and grid connected systems [10–12]. The solar panels are formed through connecting the solar cells in series and parallel to produce the required output voltage (Fig. 1). Typically, a PV cell yields less than 2 W at around 0.5 V DC. In order to increase the current output, surface area of each cell is increased or they are connected in parallel. Photovoltaic systems are chiefly used to generate power directly from the solar panels and consumed immediately and is also used to store the generated energy and utilize it later when required.

PV systems can be installed on rooftops and in deserts too. They are suitable for remote areas, where no electricity network is possible. It powers remote satellites, residences, water pumps, highway signs, navigation buoys, communication stations [13,14].

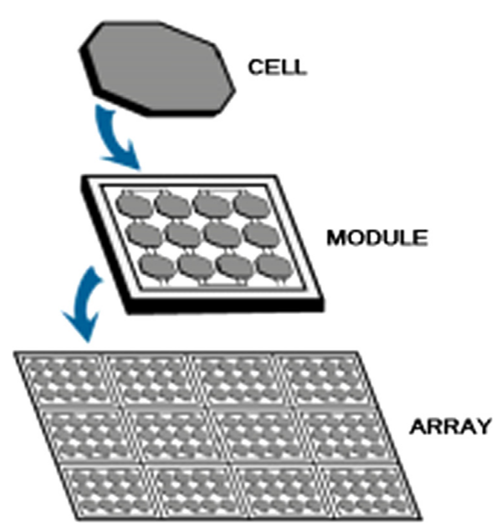

Fig. 1. Photovoltaic system.

International Energy Agency (IEA) reports [15] that around 45% of the world energy demand will be met by the solar array installations by 2050 [16].These types of installations often called as the off-grid facilities are the most economical alternative for remote and isolated locations. The PV systems are connected either to an electrical transmission grid, or to a storage energy supply. In the case of auxiliary energy, it may be supplied as heat before the power conversion, or as electricity after the power conversion [17]. The electricity that is produced can be stored in the storage batteries to extend the operating time of the system. Regardless of the load, it is essential to harvest maximum possible power through solar panels at all times [18]. In general, the PV power generation system is grid connected installations, where the generated power is supplied through the grids.

Despite the advantages of PV system, Lewis argues that the conversion technologies used in solar energy generation are costly, in addition to having scalability problems that is inherent to support a complete energy system [19]. Therefore, Kiranmayi states that it should be ensured that the PV array operates at the maximum possible conversion efficiency by taking advantage of the maximum available output of the solar array [20]. To be truly converted into a primary source of energy, solar energy should be captured effectively, converted from DC into AC or stored cost effectively for future use. Further, the changes in the radiation from sun in different weather conditions affect the solar power generated.

The factors that have an impact on the PV power system are (i) the PV panel efficiency, which was found to be in the range of 8–15% for commercial applications [15], (ii) inverter efficiency, which is at 95–98% [21], and (iii) maximum power point tracking (MPPT) algorithm efficiency, that is at 98% [22].

The PV system captures the solar energy through the solar panels. The multiple wires of the solar panels are connected through combiner box into few wires. The combiner box is connected to DC–DC converter which converts the DC input voltage into DC output voltage. The magnitude of the output voltage can be either lower or higher than that of the input voltage. The DC–DC converter is connected to DC–AC inverter which converts the DC into AC voltage. However, the DC–AC uses the electricity which it converts to operate the system [23]. Switches are connected to the input or the output of the inverter to take care of overcurrent [24]. The converters are used for different purposes including to control the variables at the load side, to regulate the flow of power in the grid connected systems and to track the maximum power available from the source [25]. Block diagram for solar inverter shown in Fig. 2.

Currently, DC–DC converters are frequently used in switching power supplies to produce the expected output power. In the past decades, a plethora of studies has been conducted to design and implement DC–DC converters which are highly efficient, especially for the home applications. Park et al. conducted experiments with 1.2 kW DC–DC converter that had a constant switching frequency of 70 kHz [26]. They concluded the study by proposing a set up DC–DC converter that had resonant voltage doubler. In order to achieve a well-controlled output voltage from a low voltage input power source, Chiu et al. produced a device that was highly efficient, low level of device stresses, and low current ripple DC–DC converter topology for solar power systems [27]. Kim et al. worked on various models to reduce power consumption of DC–DC converter and to increase the efficiency of energy conversion, the efficiency of which was compared against the DC–DC conventional converters [28]. They concluded by proposing a series connection of a module integrated DC–DC output converter with solar panel, which was connected to the output capacitor of the fly-back converter. Lee et al. proposed a novel topology for design and control of highly efficient photovoltaic DC–DC converter in an extensive load range and also drastically reduce the power rating and enhance the efficiency of photovoltaic system [29]. Choi and Lee proposed a high efficiency set up DC–DC converter in order to produce a high efficiency photovoltaic panel integrated power conditioning system (PCS) [30]. The method suggested by them comprised high efficiency DC–DC converter along with a single phase DC–AC inverter. The DC–AC converter in each of the PV panel performed MPPT thereby increasing its expandability and flexibility. The proposed system achieved 96% efficiency in DC–DC converter and the PCS achieved 93.1% efficiency.

Husna et al. studied DC–DC boost converter that uses solar system as the input source and introduced the continuous conduction mode operation for boost converter [31]. They modeled the continuous part of the converter by differential equations and state space models and at the same time state charts were used to accurately model switching actions.

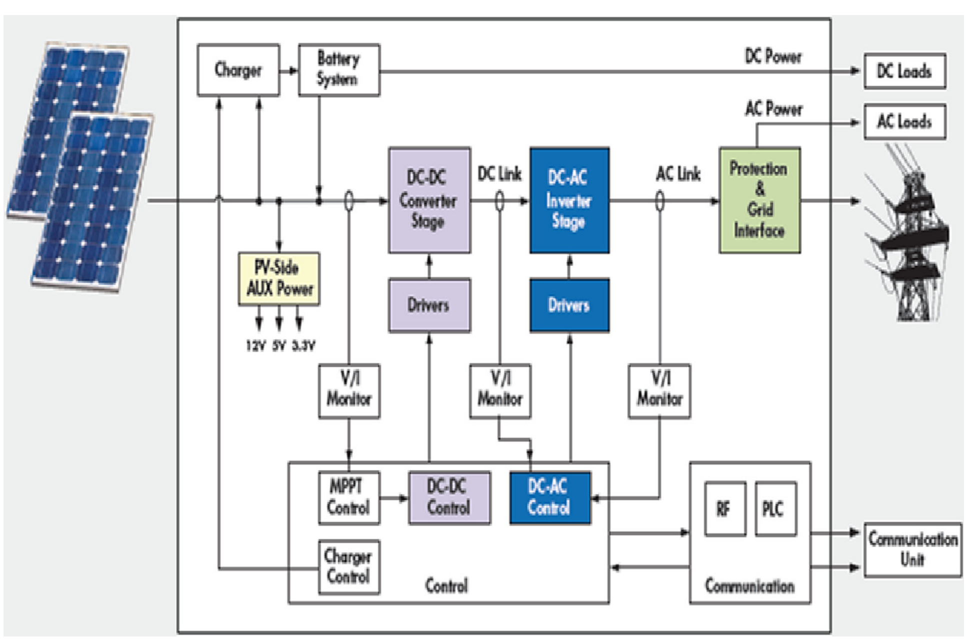

Fig. 2. Block diagram of solar inverter.

2.1. DC–DC converter based on the multi-winding transformer

Multi-input converters are used to integrate different power sources where each one of them has a different power rating. These converters accommodate a range of sources and pools in their advantage such that the energy source is diversified to enhance utilization and reliability of the renewable source [32]. Some of the advantages of the multi-input converter are reduction of size, parts count and cost, in addition to increasing the efficiency of the system [33].

A survey of the literature reveals that in the past decade, several multiple-input power electronic converter topologies have been recommended to interface traction drive needs with on-board energy sources [34,35]. Most of these methods are based on pulse width modulation (PWM), flux additivity concept, DC–DC converter for high or low voltage sources, and converters for energy storage units including batteries and ultra capacitors [36].

The principle of flux additivity can be used to derive multi-input converters, where the sources are interconnected through a multi-winding transformer. The principle helps to interconnect multiple converters which have different voltage levels [37–39]. Chen et al. proposed a novel multi-input DC–DC converter based on the transformer flux additivity concept [37]. Several advantages were observed through the circuit topology proposed by them. Some of the advantages are that the magnitude of the DC voltage need not be the same, soft-switching method is available, DC sources can deliver power both individually and concurrently and the electrical isolation is naturally achieved.

The literature reports the development of several front-end DC–DC converters that could interface the sources. These are current-fed push–pull converter [40], the interleaved boost converter [41], the three-phase converter [42], and the phase shifted full-bridge converter [43]. Subsequently, some researchers have proposed design for bi-directional converters to connect to the storage [44,45]. Nevertheless, these models have been found to be highly complex with a high cost attributed to them because of the several conversion stages and devices which were used between the individual converters [32]

Chen et al. proposed a multi-input [37], current-fed full-bridge DC–DC converter shown in Fig. 3. This converter adds up the produced magnetic flux in the magnetic core of the coupled transformer and converts it into a magnetic form in the DC input sources. The model proposed by them includes a common output-stage circuit, two current-source input stage circuits, and a three-winding coupled transformer. To meet the specification of multi-input DC sources, the input stage circuit number may be increased, while the other two components cannot be modified. The main advantage of this transformerless method is that it attains a higher efficiency while the size and weight are maintained small, in comparison with the other power generation PV systems. This method is considered to have higher efficiency than the transformer method, which is usually bulky, heavy and also not suitable for solar panel installations [46].

2.2. Interleaved soft-switching boost converter

Several reports have been published on the interleaved boost converter to reduce the input current ripples as well as the output voltage ripples in addition to decreasing the inductor and capacitor size [47]. However, in the single-switch type soft-switching boost converter, Martinez and Enjeti found it had the challenge of high voltage throughout the switch during the resonant mode [48]. Silva et al. introduced higher voltage gain boost converter, which contained the same number of semiconductor devices as that of the traditional interleaved boost arrangement, in addition to having two coupled inductors, L1 and L2. This resulted in higher output voltage [49].

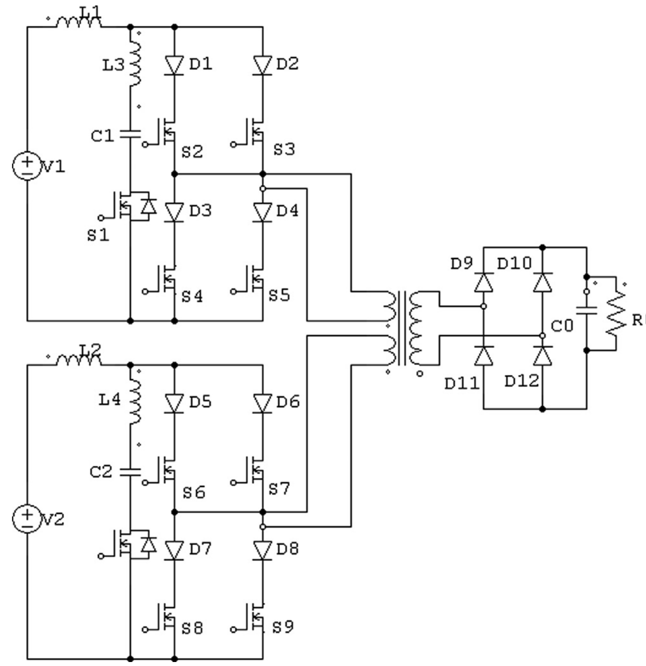

Fig. 3. Circuit topology of two-input current-fed full-bridge DC–DC converter.

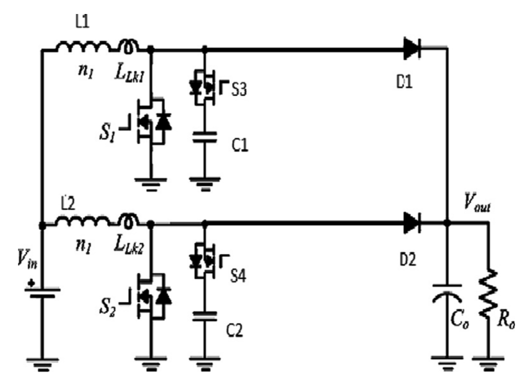

Fig. 4. Interleaved soft-switching boost converter.

In an another model proposed by Hsieh [50], there were two shunted elementary boost conversion units and an auxiliary inductor in the soft-switching interleaved boost converter. This model reduced the switching losses by turning on the active power switches at zero voltage. Unlike other complicated models, the benefit of this model was that the operation analysis and design of the converter was very simple due to the presence of two identical parallel-operated boost units.

Rezvanyvardom et al. proposed a novel interleaved Zero current switching (ZCS) PWM converter whose circuit was very simple as it used only one auxiliary switch [51]. Further, it had reduced current stresses on the main switches.

Earlier we conducted a study on the interleaved boost converter with less number of power switches based on [52,53]. Fig. 4 illustrates the interleaved soft-switching coupled inductor boost converter with active clamp. The active clamp circuit in the converter is used for reducing the leakage of energy in the coupled inductors resulting in improved efficiency. The current through the inductor is reduced to half because the total current allowed to

flow through the two inductors are the same and the inductor size is also reduced. The ripple current present in the input is less due to the presence of these coupled inductors. In Fig. 4 the L1 and L2 are the main inductors used for magnetization. S1 and S2 are the switches used for main operation and S3 and S4 for active clamping. D1 and D2 are the diodes connected to the output. The commutation of the switches S1 to S4 is done by zero voltage transition. C1 and C2 are the capacitors used for clamping. This interleaved boost converter shown in Fig. 4 is not suitable for multi-input sources due to optimum design of resonant components [122].

The advantages of an interleaved soft-switching boost converter are given below [54]:

1. The turns ratio $n2/n1$ is directly proportional to V_{out}/V_{in}. The value of turns ratio should be adjusted to produce more voltage gain. The voltage ratio is calculated by

$$G = \frac{V_{out}}{V_{in}} \tag{1}$$

$$\text{Voltage gain} = \frac{(n2/n)+1}{1-(\text{Ton}/T)} \tag{2}$$

   where V_{out} is output voltage, V_{in} is input voltage, n_1 and, n_2 are the number of turns in L1 and L2.
2. By increasing the voltage ratio, the voltage stress across the switching devices can be reduced. Thus, the overall efficiency of the system is increased by reducing the switching losses in each switch. The stress in terms of voltage can be calculated by using the following equation:

$$\text{Voltage stress} = \frac{\text{Output voltage}}{\text{Turns ratio}+1} \tag{3}$$

3. The problem of reverse recovery is reduced by using the leakage inductance present the circuit, and soft-switching is done by all the switching devices present in the circuit which reduces the switching losses.

2.3. Zero voltage switching two-input converter

Several reports have been published on the tremendous advancement of the traditional power converter topologies. The development has started with single phase interleaving which later moved to multiphase interleaving and from single level to several levels. The recent trend has been found to use single input DC–DC converters and single output converters. Besides these changes, research also focuses on multiport DC–DC converters. These are, especially, used for generating energy where varied sources and storage elements are combined and used for high power application.

The three port converter has been found to be better than conventional converters which use multiple converters. They are superior system efficiency, faster response, fewer components, compact packaging, and unified power management [55–58].

A dual active bridge topology has been found to be commonly popular among the bi-directional DC–DC converters [59,60] that use two half bridges or two full bridges in the high frequency transformer that has phase shift control ensuing in zero voltage switching (ZVS) and flexible power flow control.

Kumaran and Lakshmi investigated a high efficiency ZVS multi-input converter [61], which directly utilized the current-source type applying for both input power sources. This method proposes a reduction in conduction loss of switches in the dual-power-supply state depending on the designed PWM signals and series-connected input circuits. In order to achieve turn-on ZVS of the switches, an auxiliary circuit with small inductor functioning in discontinuous conduction mode (DCM) was used. It is possible to remove the huge reverse-recovery current of the output diode through auxiliary inductor which connected to Schottky diode [62]. Zhang et al. proposed an interleave method that can alleviate the output voltage ripple of two-input inductor currents [63]. Thus, this converter was beneficial to convert two power sources of different voltages to a single DC-bus voltage. This converter can be used both in the single and dual power supply states. The dual-power-supply state was found to be greatly efficient to reduce the conduction loss of the switches when the input circuits were connected in series along with PWM.

Nejabatkhah et al. proposed a two-input power converter (Fig. 5) that has a ZVS for a hybrid fuel cell and battery power system [64]. However, this converter could neither deliver a bi-directional functionality nor boost the input voltage, despite having well developed circuit efficiency.

Ravichandrudu et al. proposed a novel three-input DC–DC boost converter to be used for hybrid power system applications [25]. The proposed method was able to produce current-source type in the input power ports that could control the input voltages. This method was successfully used to control the power flow between the input sources and the load using duty ratios. The advantage of this converter is that it can deliver the input power sources to the load either individually or simultaneously. In comparison with the multi-source hybrid power systems, the proposed method was better in that it had simple structure, bi-directional power flow, low power components, transformer less, centralized control, high stability working point, light weight, high level of boosting and independent operation of input power sources. Table 1 shows the comparison of component requirement for various DC–DC boost converter.

3. Voltage-source inverter

3.1. Bi-directional full-bridge inverter

DC/AC power converters also referred to as inverters are chiefly used in emergency lighting systems, uninterrupted power supply

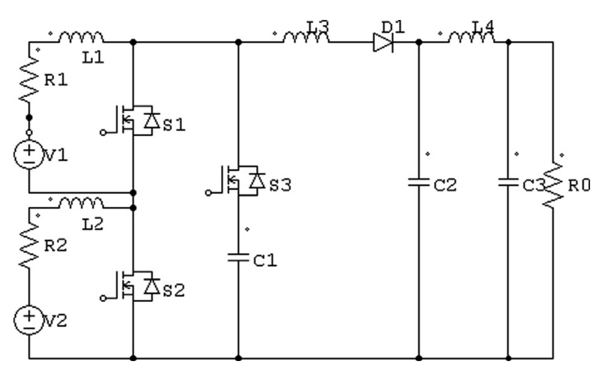

Fig. 5. Two-input converter.

Table 1
Comparison of component requirement for DC–DC converters.

DC–DC Converter Type	Number of Input Sources	Number of Switches
Transformer based converter	2	8
Interleaved converter	1	4
2 Input converter	2	3
Proposed	3	4

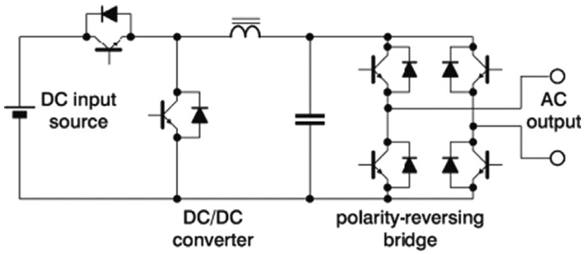

Fig. 6. Inverter using DC–DC converter and power bridge.

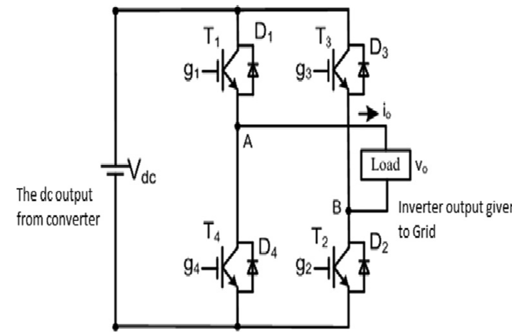

Fig. 7. Single phase full bridge inverter.

systems, adjustable speed drives, renewable energy systems, flexible AC transmission systems, voltage compensators, AC motor drive and induction heating. It derives its power from the main power to charge the battery. In case of main power failure, the inverter produces AC electricity at mains voltage from the DC battery. Thus, the main purpose of the inverter is to convert a DC input voltage to an AC output voltage having stipulated frequency and amplitude.

Resonant, soft-switching and other innovative power conversion techniques have been used to improve the efficiency of bi-directional DC–DC power converters. Bridge-type is one of the simple, commonly used inverters [65]. In the bridge-type form, the power bridge is controlled by the sinusoidal pulse width modulation (SPWM) principle that produces SPWM wave, which is filtered to generate the alternating output voltage. Fig. 6 illustrates the low frequency bridge-type inverters. For practical applications, inverters should be of portable size and light weight. However, in the bridge-type form, the problem of low direct input voltage is overcome by using large size and heavy weight that is built at a high cost, which is considered as the main drawback of this system. Reduction in size of the inverter can be obtained by using a high frequency link inverter topology [66,67]. Further, a unidirectional power flow method is used, where the power flows from DC input source to the AC output load, especially when a diode is used as a switch.

Renewable energy source systems use batteries to store the excess energy and a bi-directional power flow is required. In order to increase the efficiency of reactive loads too, bi-directional flow is expected as the reactive power is transferred back to the DC input source. Moreover, the fly-back converter that is connected at the output of DC–DC converter transfers the reactive power back to the DC input source through bi-directional power flow. The delay which occurs as a result of the reactive power sensing and control enables the increase in output voltage distortion [68]. It is well-known that the output gained from the PV cell is not stable as it is impacted by the variations in the temperature of the sun's rays received by the panels. The storage elements of the inverter improve the system dynamic properties through absorbing the energy fluctuations thus stabilizing the output attained from the PV cell. The DC obtained as the output obtained from the boost converter cannot be directly fed to the grid [69,70]. Koutroulis et al. [71] considerably reduced the distortion due to harmonics in the output by using the pulse width modulation based voltage-source inverter to convert the DC voltage into sinusoidal output.

In classical voltage-source inverter (Fig. 7), the AC output voltage is lower than the DC input voltage. To overcome this challenge, Caceres & Barbi proposed a boost DC–AC converter that could generate an AC output voltage much larger the DC input voltage [72]. They introduced a sliding mode controller to ensure that boost converter works at its optimum at all working conditions. This model is unique for its robust nature for parameter variations in the plant and, therefore, have an invariant dynamics and steady-state response in the ideal case.

Table 2
Comparison of component requirements for one leg of five level inverter.

Converter type	Diode clamp	Flying capacitors	Cascaded inverters
Main switches	8	8	8
Diodes for clamping	12	0	0
Main diodes	8	8	8
Capacitors (C_{dc})	4	4	2
Capacitors for balancing	0	6	0

3.2. Multilevel inverter

Multilevel inverters have been studied with great interest due to their capability to operate at high voltage, high efficiency, low switching losses and low output of electromagnetic interference [73]. In the case of multilevel inverters, more than two DC voltage levels are used to synthesize the output. As the number of sources increase, the inverter voltage waveform reaches a nearly sinusoidal waveform when a low switching frequency parameter is used, thus resulting in low switching losses [74]. This technology has found applicability in many power electric devices especially to generate power commercially [75].

Several multilevel inverters are cited in the literature: diode clamped (neutral clamp), capacitor clamp (flying capacitor), and cascaded H-bridge multilevel inverters. The diode clamped type multilevel inverter uses three levels [76]. This type of multilevel inverter is commonly used in many industries but has been found to have an unbalanced capacitor voltage when the number of levels was increased. In the case of flying capacitor type, the number of capacitors are directly proportional to the number of levels, due to which, more number of capacitors are used leading to complication in the inverter control scheme. In addition, these power capacitors also become bulky and costly.

In comparison to diode clamped and flying capacitor type, the cascaded H-bridge multilevel inverter required fewer components to obtain a similar number of voltage levels [77]. Table 2 depicts the comparisons of component requirements per leg of multilevel inverters.

Leon et al. have demonstrated the application of multilevel inverters for photovoltaic power conversion system [78]. Using five output voltage levels H-bridge inverter with multisampling and with reduced quantities of switching devices, they have shown that multilevel inverters reduce the total harmonic distortion and gives high efficiency and power factor.

Some have proposed multilevel inverters that use IGBTs to replace the GTO-based two-level inverters in medium-voltage applications. In comparison to GTOs, IGBTs were able not only to switch faster but also have less demanding gate drive specifications.

Therefore, IGBT based inverters were able to significantly decrease the weight and size of the passive filter components and provide much better voltage waveforms. The number of switches increased in an order of $2m-1$ with the number of voltage levels for diode clamped, flying capacitor and cascaded H-bridge multilevel inverters.

3.2.1. Cascaded H-bridge inverter

In one of our previous works, we had used multilevel inverter at the second stage of power conversion. This multi-level inverter comprised two H-bridge inverters that were cascaded together. The output of the cascaded H-bridges was equal to half of one H-bridge inverter. By using small sized inductors, current ripples were found to be effectively filtered out by this multilevel inverter. Compared to bipolar type inverters, these inverters were able to reduce maximum current ripples when the duty ratio as at 50%. A single level H-bridge inverter and a five level multilevel inverter PWM technique along with phase shift were used for the study (Fig. 8).

With increased number of switches the current ripple frequency got increased by this phase shifted PWM technique. However the switching frequency of the switches could not be increased due to practical constraints. Depending upon the phase shifted carriers, a multisampling technique was followed to reduce this current ripples. The purpose of multisampling is to reduce the delay during PWM. Many PWM techniques with improved performance were employed for the inverter by [79].

An improved closed-loop control gain was observed in multilevel inverter than in bipolar type inverters. Similarly, in comparison to switched type inverter, the steady state was reached shortly by the H-bridge multilevel inverter [121]. For symmetric type inverter the levels of output voltage can be calculated using

$$V_{\text{level}} = 2N+1 \tag{4}$$

where $N=1, 2, \dots i$ (Number of inverters in cascaded connection)

$$V_{\text{omax}} = NV_{\text{dc}} \tag{5}$$

where V_{dc}=input dc voltage and V_{omax}=maximum output voltage.

$$V_{\text{omax}} = 5V_{\text{dc}} \tag{6}$$

where $N=5$ in five level inverter.

The asymmetric type inverters give more number of voltage levels when compared to the symmetric type multilevel inverter.

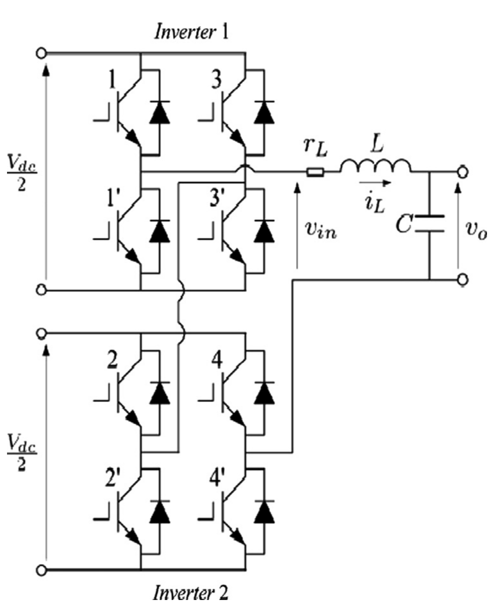

Fig. 8. Five level cascaded H-bridge inverter.

The output voltage level can be calculated by

$$V_{\text{level}} = 2^{n+1}-1 \tag{7}$$

If $V_i=2^{i-1}V_{\text{dc}}$, $i=1, 2, 3, \dots, n$

$$V_{\text{omax}} = (2^n-1)V_{\text{dc}} \tag{8}$$

$$V_{\text{level}} = 3^n \tag{9}$$

If $V_i=3^{i-1}V_{\text{dc}}$, $i=1, 2, 3, \dots, n$

$$V_{\text{omax}} = \frac{(3^n-1)}{2}V_{\text{dc}} \tag{10}$$

3.3. Matrix inverter

Matrix inverter concept was first introduced by Baker and Bannister in 1975. Though multilevel commenced with three-level [76], later several level topologies were developed [80,81]. A matrix converter has a 3-phase to 3-phase configuration with one of the feasible direct AC–AC topology built into its basic structure [82]. Matrix converter is superior to traditional inverter power converters in many ways: provides sinusoidal input as well as output waveforms; has very few higher order harmonics; no subharmonics; inherently bi-directional energy flow capability; fully controllable input power factor; minimum energy storage requirements; and no bulky and lifetime limited energy storing capacitors [83].

Bendiabdellah and Bachir compared the performance of the matrix converter with the three-level inverter for the R–L load case and induction motor case [84]. As they did not find much difference between the two inverters, they recommended the substitution of matrix converter for three-level inverter for industrial applications. They believe that matrix converter was better than multilevel inverter especially for high power and high voltage applications. The technical advantages of matrix converter over three-level inverters were realized through as a direct synthesizing of the required voltage; thereby, eliminating the intermediate stage and the output filter. Further, the number of switches was reduced from 30 to 9 components in matrix converter. Consequently, a much less complicated system is obtained.

The main drawback of the matrix converter is its limited (87%) maximum input output voltage transfer ratio for the sinusoidal input and output waveforms. Further, in comparison with traditional AC–AC indirect power frequency converter, it needs more semiconductor devices due to the absence of monolithic bi-directional switches. Discrete unidirectional devices are utilized for each bi-directional switch. Any disturbances in the input voltage system have an impact on the performance of the matrix converter [83]. However, due to the several advantages, extensive research is being conducted on matrix converters for the realization of highly compact three-phase AC drives used for multiple applications including industrial, military, marine and avionics systems [85].

Review of the available literature shows that most of the research on matrix converter has been conducted on the digital generation of the PWM switching patterns and modulation schemes [83,86] proposed an AC–AC sparse matrix converter that was equivalent to traditional AC–AC matrix converter. The proposed converter had no energy storage elements and had only 15 IGBTs, and in the case when only unidirectional power flow is required, the component reduced to six.

Miller proposed a three-phase six switch voltage-source converter to be used in medium to high power applications[87]. This proposed converter can generate any current waveform and function as a bi-directional active power flow inverter or rectifier

Table 3
Comparison of controlled and uncontrolled switch based inverters.

Inverter type	DC output voltage	Ripples in %	Number of Switches	Total Harmonic distortion in %
3 Phase full bridge diode inverter	$V_{dc}=\frac{3}{\pi}\sqrt{2}V_{ll}$	± 5	6 Diodes	30
3 Phase double bridge diode inverter	$V_{dc}=\frac{6}{\pi}\sqrt{2}V_{ll}$	± 1.15	12 Diodes	12
3 Phase full bridge controlled inverter	$V_{dc}=\frac{3}{\pi}V_{ll}\sqrt{2}\cos\alpha$	More accurate and less ripples	6 IGBT's	5.74

at the time absorbing bi-directional reactive power flow. This inverter can operate at all four quadrants of the P–Q plane.

The DC-bus voltage requires stabilization to a specific value in the inverter. Similarly, energy from PV modules should be fed into the utility grid by converting the DC current into a sinusoidal waveform. These features allow for the application of gird-connected PWM voltage-source inverters in PV systems. Table 3 shows the comparison of controlled and uncontrolled switch based inverters.

4. Controllers used for DC–DC converter

DC–DC power converters are used to achieve a stabilized output voltage which may be lower (buck) or higher (boost) or generic (buck–boost) from the input voltage. DC–DC converters are simple to operate due to less number of components used in it. Yet, these converters need controllers which can control the circuit to ensure stabilization of load and input voltage, maintain component tolerance and system ageing [88].

Boost converters are used to achieve higher output voltages than that of input DC voltage. They are especially used in PV solar systems, battery sources, and fuel cells [89]. Zaitu reported that these converters are not suitable for open-loop condition, as they could not regulate voltage to the expected level and due to its inadequate dynamic response [90]. Therefore, this coverter uses a closed-loop control for the regulation of output voltage. In order to achieve the required output voltage, several control strategies have been reported in the literature, which vary from ON to OFF state of the switch. In the past, the linear controllers, such as P, PI, and PID, were designed standard frequency response techniques. These techniques were based on small-signal model and performed well at the operating point but could not provide a good large-signal transient [91]. Similarly, closed-loop controllers were used for small-signal linearlization.

Accurate and reliable regulation of voltage is essential; therefore, several kinds of voltage regulators along with different control modes have been used to increase the efficiency of DC–DC converters. Consequently, Buck, Boost, Buck and Boost, Cuk and fly-back have been developed to meet the demands of the tasks. Further, no one technique can satisfy the different specification of all converters.

Two important control methods available for DC–DC converters are voltage mode control and current-mode control. Voltage control mode is a single loop controller which is connected to a reference voltage. The output voltage of the converter is measured and compared to the reference voltage in order to generate voltage error signal. Depending on the error signal obtained, the duty cycle is adjusted to ensure that the output voltage matches the reference value. This method is often used in industrial applications as well as in research as it is easy to implement [92]. Voltage mode controllers have the frequency response methods built into its design for DC–DC converters (Fig. 9).

On the other hand, current-mode controller is a two loop system wherein an extra inner current loop is connected to the voltage loop. This extra current loop senses the inductor current and controls the duty cycle. It compares the inductor current to the reference value, which is generated by the voltage loop, with the control signal and generates a duty cycle of a specific frequency that drives the switch of the converter [93] (Fig. 10).

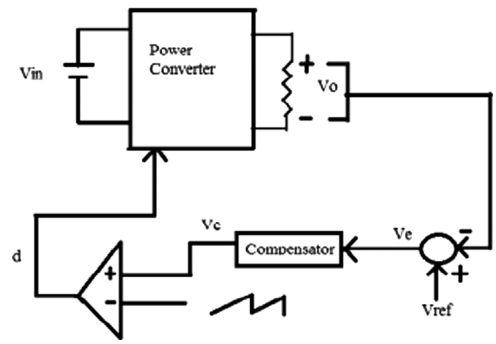

Fig. 9. Voltage mode control of DC–DC converters.

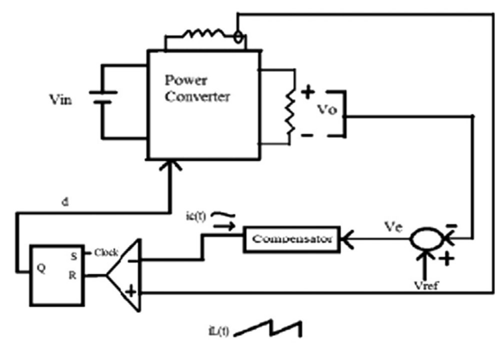

Fig. 10. Current-mode control of DC–DC converters.

4.1. Sliding mode control (non-linear controller)

As DC–DC converters are non-linear and time variant, they are not suitable for linear control theory; hence, they can be controlled by sliding mode control (SMC),which is derived from the variable structure control system theory (VSCS) [94]. It applies the discontinuous control signal that makes the system "slide" along a crosssection of the system's normal behavior. Tan et al. proposed a fixed frequency SMC that was based on indirect SMC and implemented in PWM form [95]. The SMC was proposed especially for boost-type converters that required (i) wide operating conditions and could not be controlled by PWM current-mode controller and (ii) fast response which could not be controlled by either other SMC or non-linear voltage type of controllers.

As the traditional SMC implementation is based on hysteresis modulation (HM), they needed a bang–bang type of controller to perform the switching control [96]. This SMC is extremely controlling sensitive to noise and has varying switching-frequency operation. These drawbacks can be overcome by applying constant timer circuits, inject a synchronizing signal into the hysteric controller or implement adaptive hysteresis band control. Nevertheless, these solutions increase the number of components used

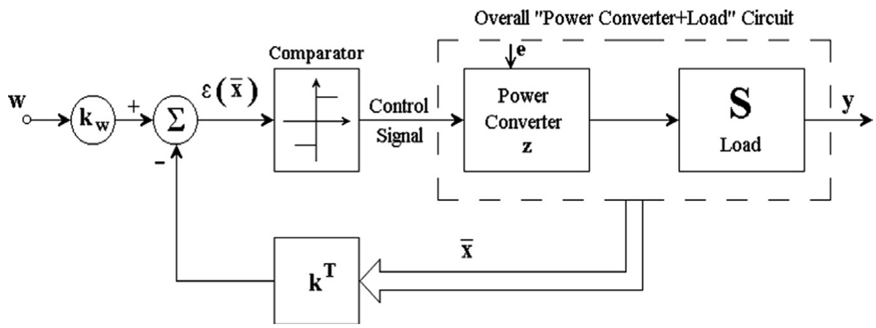

Fig. 11. Block diagram of a variable structure non-linear system using SMC.

and is also not particularly suitable for low cost voltage conversion applications. Adding an integral loop in the voltage error and using an adaptation system can help in getting over the disadvantages [97].

Bühler suggested a block diagram model for variable structure system (VSC) by utilizing SMC [98]. In this model, the DC–DC power converter is signified by a switch and its reactive elements are encompassed in the load. Since this block diagram was useful only if the reactive elements of the converter were kept behind the switch, Stanciu proposed a model that could be used even when the reactive components are placed in front of and also behind the switches. In the proposed model, the power block is not used as a switch but as a power converter holding static switches and passive elements (R, L, and C) (refer Fig. 11). In this model, the supply voltage "*e*" and the control signal of the converter static switches determine its state. Switching function "*z*" which is part of the power converter considers the state of the circuit switches, whose state is ascertained by the comparator.

4.2. PID controller (linear)

Proportional integral derivative (PID) control, which is one of the oldest control techniques, uses P, PD, PI or PID controllers, which enable the regulation of DC power supply in the converters [99,100]. The chief functions of the PID involves providing feedback, anticipating the future action through derivative action and eliminating steady state offsets by integral action. Most of the control problems, including modest performance requirements, can be addressed through PID [101]. The design methods differ with respect to the knowledge of the process dynamics they require. A PI controller is described by two parameters (K_p is the proportional gain, K_i integral gain) and a PID controller by three or four parameters (K_p is the proportional gain, K_i integral gain, K_d derivative gain, and Time *Ts*). PI controller is designed for buck converter that operates during a start up transient, while the PID is designed to be used during and steady state. Process dynamics of PID are categorized by two parameters: one that is associated with the process gain and the other describes how fast the process is. In the step response method, the parameters have simple characteristics that are obtained from the step response. In the frequency response method, it is characterized by the parameters, the ultimate gain and the ultimate frequency [102].

PID control involves three separate parameters, namely the proportional, the integral and derivatives. The proportional term also known as "gain" makes a change to the output that is proportional to the current error value. The integral term also known as "reset" contribution is proportional to the magnitude and duration of error. The rate of change of the process error is calculated by determining the slope of the error over time and multiplying this rate of change by derivative gain K_d, also known as "rate". The constant values are added to calculate the output of the PID controller, which is the manipulated variable (MV) using the following equation:

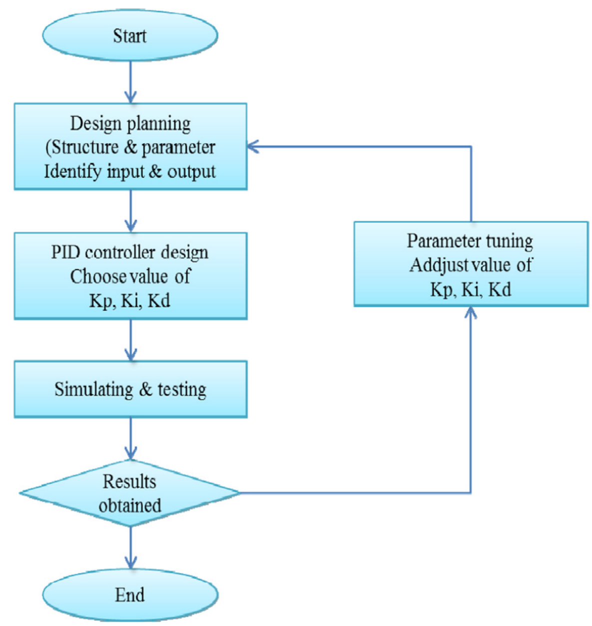

Fig. 12. PID controller process flow.

$$MV(t) = P_{out} + I_{out} + D_{out} \tag{11}$$

where P_{out}, I_{out}, and D_{out} are the contributions made by the PID controller to the output from each of the three terms. Adjusting the proportion, integral and derivative values of the PID controller algorithm, the control action designed for specific process requirements can be met (Fig. 12).

The controller's response can be explained with respect to (i) the responsiveness of the controller to an error, (ii) the degree to which the controller overshoots the set point and (iii) the degree of system oscillation. Similar to SMC, the PID controller's derivative term is also liable to noise and measurement error of the system that might result in oscillation of the duty cycle during steady state [103].

$$u(t) = K_p e(t) + K_i \int_0^t e(t)\,dt + K_d \frac{d}{dt} e(t) \tag{12}$$

where, K_p is the proportional gain; $K_{i,}$ integral gain; K_d, derivative gain; *e*, error = SP − PV; *t*, time or instantaneous time (the present), and τ, variable of integration, takes on values from time zero to the present *t*. Fig. 13 illustrates the block diagram of PID controller.

4.3. Fuzzy logic controller

Literature on fuzzy logic control has been abounding due to the various developments made in that area. Recently, the fuzzy logic theory has found application in water quality control [104], automatic train operating system [105], elevator control, etc.

In a fuzzy logic controller (FLC), the linguistic control rules are related to each other through the dual concepts of fuzzy implication and the compositional rule of inference. Thus, based on expert knowledge, an algorithm is created in FLC that can convert the linguistic control strategy into an automatic control strategy [106]. FLC is better than the conventional control algorithms particularly for complex processes that could not be analyzed using conventional quantitative techniques. Thus, Gupta and Tsukamoto considered FLC as a union between conventional precise mathematical control and human-like decision making [107].

Wai et al. has described the four main components of the FLC [108]. (i) fuzzifier acts as an interface to convert the input data into required linguistic values, (ii) inference engine is a software code that processes the cases, rules, objects or other knowledge or expertise based on the facts of a particular situation, (iii) Rule Base and Data Base known as the knowledge base contains database with necessary linguistic definition and control rule set, and (iv) defuzzyfication, which it reverse of Fuzzyfication, produces required output in a linguistic variable (fuzzy number). Decision making simulates the human decision process and derives the fuzzy control action from the knowledge of the control rules and the linguistic variable definition (Fig. 14).

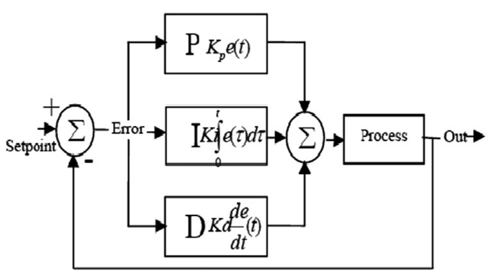

Fig. 13. Block diagram of PID controller.

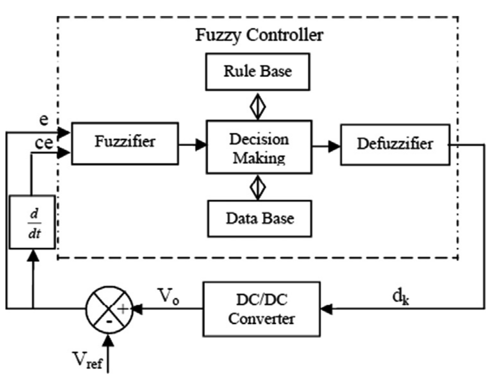

Fig. 14. Fuzzy logic controller.

The error e and change of error ce are inputs for the FLC defined by the following equation as:

$$e = V_o - V_{ref} \tag{13}$$

$$ce = e_k - e_{k-1} \tag{14}$$

where V_o is the present output voltage, V_{ref}, the reference output voltage, and k, values taken at the beginning of the kth switching cycle. The output of the fuzzy controller is the duty cycle and is defined in equation as

$$d_k = d_{k-1} + \eta\delta\, d_k \tag{15}$$

where δd_k is the duty cycle inferred change in the kth sampling time of fuzzy controller and η is the fuzzy controller gain factor.

According to [109], the performance of FLC is better than PID controllers in terms of peak time, rise time, settling time and robustness. FLC produces less voltage deviation from voltage reference variation. Further, due to more damping, less overshoot, and its sensitive nature towards parameters it works better in dynamic conditions. FLC can be implemented in buck converters as well as in several converter topologies. Another significant advantage is its fast response along with of higher accuracy. FLC has many advantages over the conventional PID and can be implemented in DC–DC converters to improve its efficiency. Table 4 and Fig. 15 show the comparison of FLC and PID controllers.

5. Modulation techniques for three-phase VSC

Three-phase VSC has been a subject of great interest for research as it is the most widely used three-phase topology for medium to high power applications. Literature reports different modulation techniques being used in the past for improving performance of the converter. Some of these are discussed in this section.

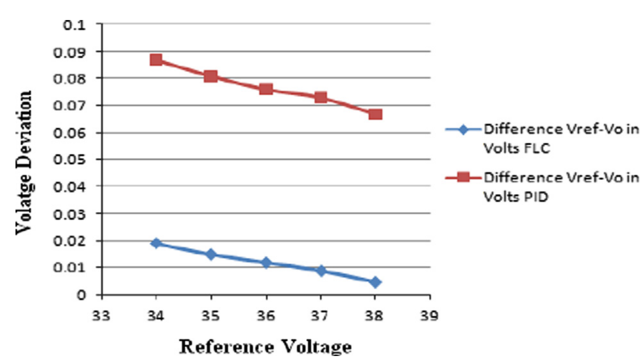

Fig. 15. Fuzzy controller vs PID controller.

Table 4
Comparison of FLC and PID controllers.

Dc input voltage in volts	Reference voltage in volts	Duty cycle in %	DC output voltage PID in volts	Difference $V_{ref}-V_o$ in volts	DC output voltage FLC in volts	Difference $V_{ref}-V_o$ in volts
48	38	60	38.067	0.067	38.005	0.005
48	37	55	37.073	0.073	37.009	0.009
48	36	50	36.076	0.076	36.012	0.012
48	35	45	35.081	0.081	35.015	0.015
48	34	40	34.087	0.087	34.019	0.019

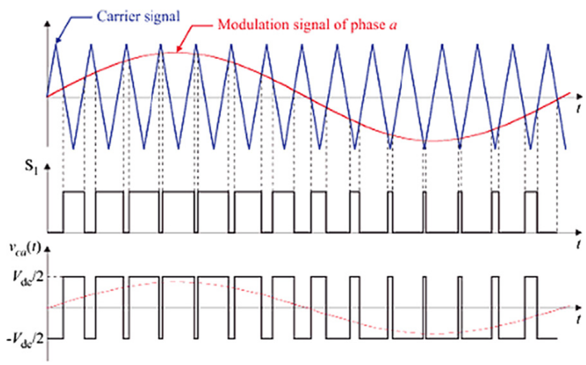

Fig. 16. Naturally sampled carrier-based modulation.

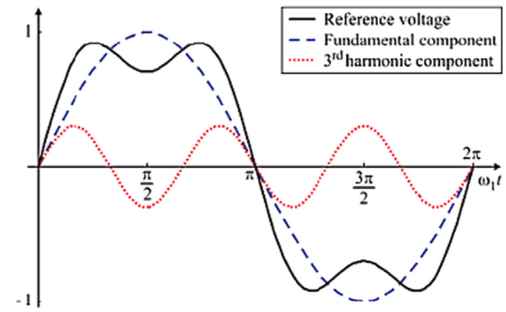

Fig. 17. Reference voltage along with fundamental component and third harmonic component.

5.1. Naturally sampled carrier-based modulation

Modulation of three-phase voltage-source converter is commonly done through naturally sampled carrier-based modulation. In this strategy, the low frequency modulation signal in the sinusoidal wave form is compared to the high frequency carrier signal. Drive signals for the switches of the converters are obtained as the output of the comparison. Sawtooth and triangular waveforms were obtained as the common carrier signals. A sawtooth carrier signal modulated the trailing edge of the drive signal, whereas the triangular carrier signal not only modulated the trailing edge but also the leading edges of the drive signals. Thus, triangular carrier signal enhanced the harmonic performance better than the sawtooth carrier signal. When the amplitude of the modulation signal is greater than the carrier signal, it turns on the high-side switch of the phase leg, consequently, connecting the mid-point of the phase leg to the positive rail of the DC link. On the contrary, when amplitude of the modulation signal is lower than the carrier signal, it turns on the low-side switch of the phase leg, thus connecting the mid-point of the phase leg to the negative rail of the DC link. Comparison of the carrier signal with that of the modulating signal generates a high frequency modulated voltage between the mid-points of the phase leg and that of the DC link (Fig. 16).

5.2. Sinusoidal pulse width modulation

The SPWM form is also called as the sub-harmonic, triangulation or sub-oscillation method. It is popular in industrial applications and has gained a lot of attention in research and thus reviewed extensively in the literature [110].

Though several pulse width modulation methods are available, SPWM were found to be commonly used due to its superior performance. In this method, the DC link is maintained at constant using front-end converter and the frequency of the output voltage is controlled within the inverter through pulse width modulation technique. To generate a variable output voltage that contains low-harmonic content, it is ensured that the inverter power devices are switched “ON” and “OFF” several times within a given half-cycle. The triangle carrier wave helps in the implementation analog that compares it with a sine wave reference signal. The instants of commutation are decided by the crossover points. By varying the modulation index, it is possible to change the amplitude of the output voltage. In case of the modulation index being lower than unity, only carrier-frequency harmonics in addition to fundamental-frequency-related side bands appear in the output. Moreover, it is possible to increase the voltage above the modulation index of unity till the maximum voltage is reached in square wave mode [111].

Fig. 17 illustrates the SPWM concept, where the pulses in the output form have been found to have a sine weighting equivalent

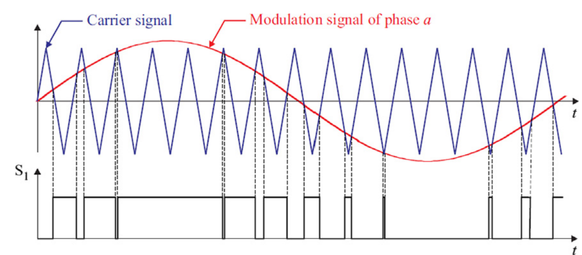

Fig. 18. Over-modulation.

to the reference waveform. Though this method was first used along with analog circuits, the digital implementation is preferred now.

An essential component that is proportional to the amplitude of the reference sine wave is demonstrated when the harmonic analysis of the waveform is made. In addition to that uncontrolled and large harmonic components were observed at the carrier frequency. When the frequency was increased the effect of the carrier-frequency harmonic was reduced, which may be related to the effect which is largely limited by the frequency dependent motor reactance. Thus, the frequency which is at the highest for the inverter was found to be the best to be used for practical purposes. These are implemented in digital systems that use up-down counters instead of the triangular waveform and lookup tables to determine the reference value at any point.

The modulation depth or modulation index for phases *a*, *b*, and *c* is $0 \leq M \leq 1$ and for a carrier signal of amplitude which is equal to 1.

For operation in the linear mode, the amplitude of the reference voltages must be equal or smaller to the amplitude of the carrier signal. The maximum line to line converter voltage for $M=1$ is $\sqrt{3}V_{dc}/2$, that is, 86.6% of $V_{dc}/2$. If $M>1$, then the converter operates in over-modulation (non-linear mode). In over-modulation, the converter voltages saturate and a non-linear gain are presented by the voltage-source converter. The over-modulation is illustrated in Fig. 18. However, over-modulation is detrimental as it generates sub-carrier harmonic currents which can deteriorate the performance of current controller [112].

Space vector modulation (SVM) for a three-phase inverter helps it to adapt the switching behavior to many different situations including full-load, half-load, linear and non-linear load, pulsating load, static load, etc. SVM is able to eliminate the lower order harmonics that is not possible by filters. The space vector PWM technique produces a 15% increment in maximum voltage when compared with the PWM thus enabling efficient use of the DC voltage. The output performance of SVM is exceptionally good with high reliability and optimized efficiency, when compared to other similar inverters that have conventional PWM [113].

5.3. Space vector modulation

In the beginning, SVM method was developed as a vector approach to PWM for three-phase inverters. Depending on the location of the output voltage vector, the space vectors are applied. The switching instants can be determined through space vector modulation technique depending on the representation of switching vectors in α–β plane. SVM enhances the output efficiency of the SPWM without distorting output voltage wave. It, thus, avoids unnecessary switching [114].The fundamental principle of carrier-based modulation and SVM is the same, wherein the average value of the voltage is controlled by them on a cycle-by-cycle basis. A suitable selection of the carrier and modulation signals would produce the SVM. Likewise, carrier-based modulation strategies may also be executed in the SVM by evaluating the suitable voltage space vector sequence.

In SVM, the currents and the time domain voltages of the converter are represented as the stationary α–β plane, a rotating vectors in an alternative reference frame. The Park transform or the abc to $\alpha\beta0$ transformation converts the time domain quantities to the new reference plane. The three-phase voltages or currents are transformed into a single space vector that rotates around the α–β plane at the line frequency. Time is implicit in the angular position of the space vector in the $\alpha\beta$ plane.

6. Proposed grid integration scheme

Meeting energy demand that is growing exponentially and providing continuous supply is a crucial political issue across the globe. Adding to this woe is the explosion of the population especially in developing countries. Though a decline in the world population growth rate is expected, India is expected to increase its population by 300 million between 2010 and 2040 and African countries by 800 million in the same period. An estimated 50% increase in household numbers implies that it will act as driver to boost energy demand. More household means more energy requirements for electronic devices, air conditioning, heating, etc. Another aspect of concern is the shifting of population to urban areas, the impact of which is evident in China where 1.3 billion live in cities. In similar standards, economic growth and rise in living standards will augment energy requirement (Fig. 19). The impact of energy demand on the transport sector and industry sector anticipated to remain on a smaller scale [115].

The world energy demand in 2040 will be around 700 quadrillion BTUs, i.e., it will be 35% more than what was required in 2010. The silver lining in this scenario is that the energy demand does not proportionately increase with economic growth as there is improvement in energy efficiency and change in the economic structure over time.

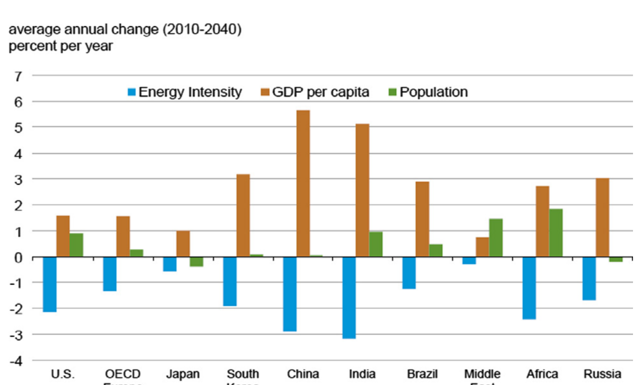

Fig. 19. Energy demand in relation to economic activity and population. Source: EIA, International Energy Outlook 2013.

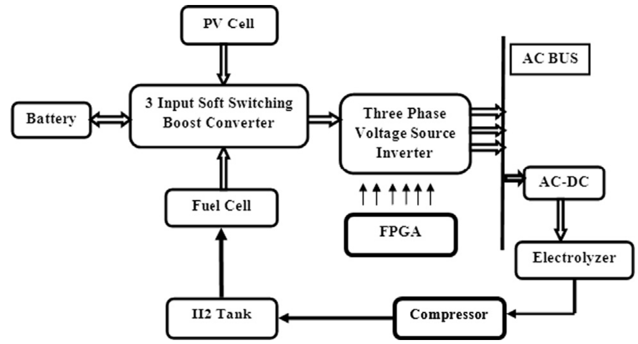

Fig. 20. Block diagram of proposed grid connected topology.

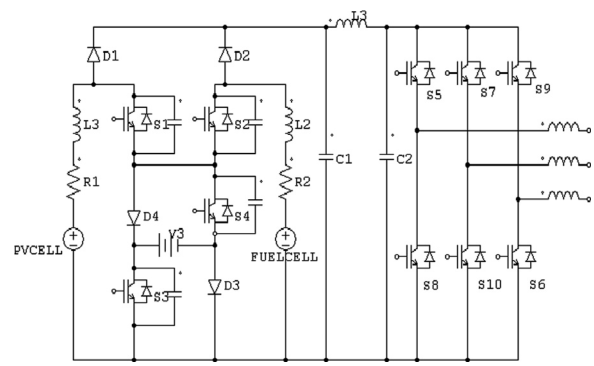

Fig. 21. Novel grid connected topology.

The grid-connected PV system frequently uses a series of mixture of PV arrays to directly convert sunlight to DC power and a converter to convert DC to AC power. The converter is also involved in keeping the PVs functioning at maximum efficiency. In addition to these components, super capacitors and batteries are used as storage devices in the PV systems. These components play a role in enhancing the power generation at night, reactive controlling over the PV systems, and voltage stabilizing of grids [116,117].In this research, energy was generated using PV cells, FCs and battery as inputs. PV cell and FCs were connected unidirectionally to the booster. Two lead acid electric batteries of 12 V were connected in series to the booster bidirectionally to obtain 24 V, which was used as storage system. Since the maximum possible DC energy produced through FC and PV cell was 35 V and 40 V, respectively, a booster was required to produce the stipulated 230 V and 50/60 Hz AC supply. We used three input boost converter with soft switching technique to convert the lower DC input voltage into higher output DC voltage [118]. The system was further converted to AC and matched with grid to operate it as a grid-connected system. The AC voltage was obtained by using three-phase VSI along with pulse width modulation technique and synchronized utility grid as per [119,120]. Fig. 20 illustrates the energy generation process in the proposed system.

Fig. 21 illustrates the circuit containing boost converter with three inputs [118]. In the circuit, two of the power inputs are linked with the current source type converter, which enhances the voltage of the power input sources. The control of power from PV is achieved by the duty cycle of IGBT1. The best possible power flow in the FC is attained by varying the duty cycle of IGBT2. All the power devices present in the circuit are restricted with separate duty cycles. Controlling of duty cycles ensures the power flow among the sources and between the source and load. The battery is charged and discharged from PV and FCs assisted by converter. Charging and discharging of storage element is maintained by varying the duty cycle of IGBT3 and IGBT4.

7. Conclusions

This review analyzed the literature to understand the use of converters in the PV systems. Several studies have been conducted in the past to design and implement DC–DC converters which are highly efficient. The DC–DC boost converter that uses solar system as the input source and introduced the continuous conduction mode operation for boost converter was reviewed. It has been found that the multi-input converters had advantages like reduction of size, parts count and cost, in addition to increasing the efficiency of the system. Past studies have shown that multi-input converters were based on PWM, flux additivity concept, DC–DC converter for high or low voltage sources, and converters for energy storage units including batteries and ultra capacitors. Interleaved soft-switching boost converters were found to be used for reducing the input current and output voltage ripples and decreasing the inductor and capacitor size. Several models have been proposed by many researchers to increase efficiency. The model which we had proposed earlier along with its advantage over other models has been discussed in detail. The progress of ZVS from two-input through three-input and multi-input converter has been discussed in detailed. The voltage-source inverter types like bi-directional full-bridge inverter, multilevel inverter and matrix inverter were reviewed. The advantage and the drawbacks of these inverters are provided to understand their efficiency. Further, the controllers used for DC–DC converter and the voltage-source inverter are described in-depth with the advantages of different methods adopted.

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